US010985611B2

(12) **United States Patent**
Sagi et al.

(10) **Patent No.: US 10,985,611 B2**
(45) **Date of Patent: Apr. 20, 2021**

(54) **SYSTEM AND METHOD FOR ESTIMATING GRID STRENGTH**

(71) Applicant: **General Electric Company**, Schenectady, NY (US)

(72) Inventors: **Deepak Raj Sagi**, Bangalore (IN); **Kasi Viswanadha Raju Gadiraju**, Bangalore (IN); **Deepak Aravind**, Bangalore (IN); **Vaidhya Nath Venkitanarayanan**, Schenectady, NY (US)

(73) Assignee: **General Electric Company**, Schenectady, NY (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 86 days.

(21) Appl. No.: **16/379,933**

(22) Filed: **Apr. 10, 2019**

(65) **Prior Publication Data**

US 2020/0328611 A1 Oct. 15, 2020

(51) **Int. Cl.**

H02J 13/00	(2006.01)
G05B 19/042	(2006.01)
H02J 3/38	(2006.01)

(52) **U.S. Cl.**

CPC .... ***H02J 13/0006*** (2013.01); ***G05B 19/042*** (2013.01); ***H02J 3/386*** (2013.01); (Continued)

(58) **Field of Classification Search**

None

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,174,150	B2	5/2012	Delmerico et al.
8,509,958	B2	8/2013	Larsen et al.

(Continued)

FOREIGN PATENT DOCUMENTS

CN	103036498 B	4/2013
DE	102017112944	12/2018

(Continued)

OTHER PUBLICATIONS

Huang et al., Voltage Control Challenges on Weak Grids with High Penetration of Wind Generation: ERCOT Experience, Conference: Power and Energy Society General Meeting 2012 IEEE, Research Gate, Jul. 2012, San Diego, CA, pp. 1-7.

(Continued)

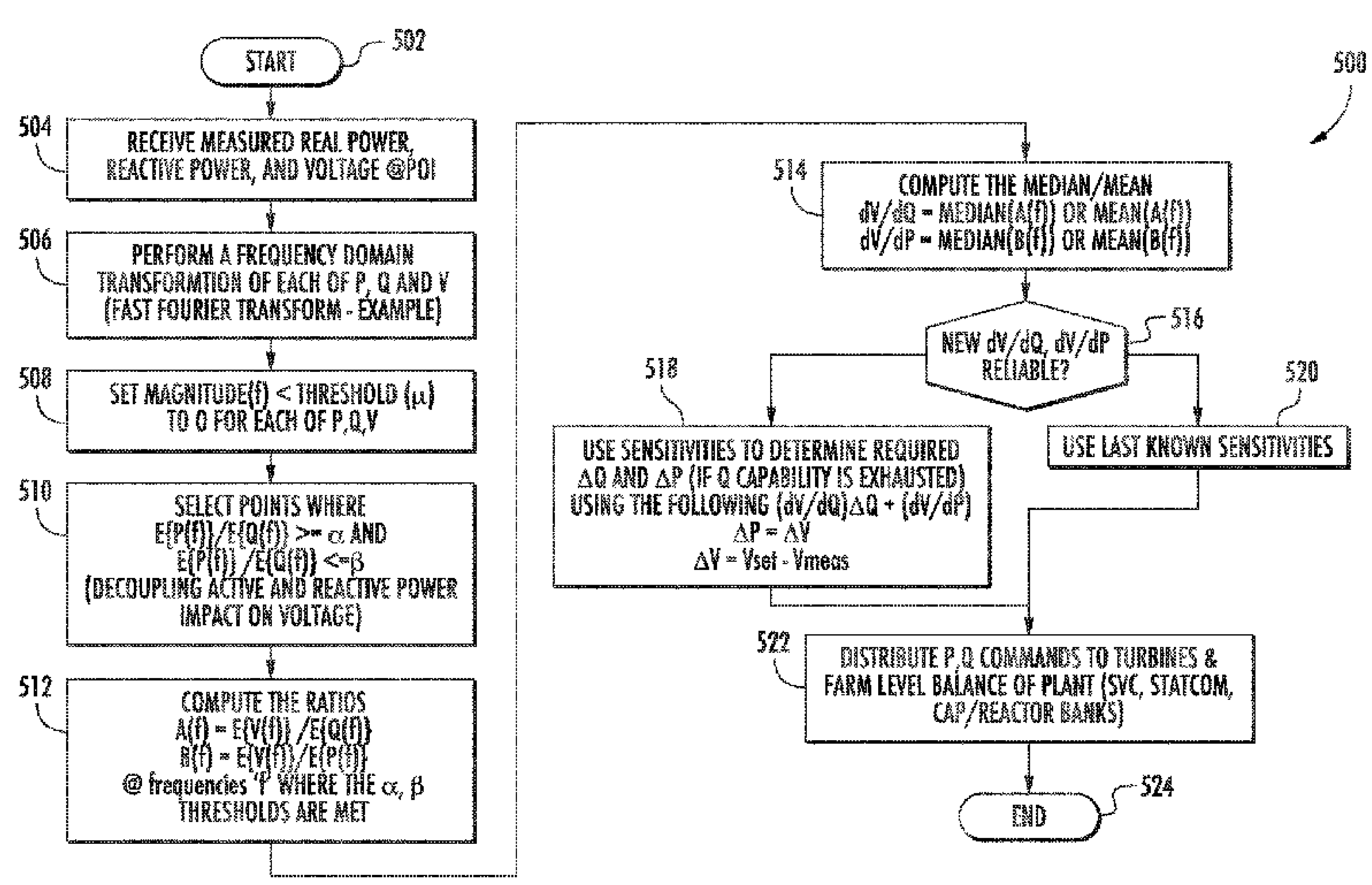
Primary Examiner — Paul B Yanchus, III

(74) *Attorney, Agent, or Firm* — Dority & Manning, P.A.

(57) **ABSTRACT**

A method for estimating grid strength of a power grid connected to a renewable energy farm having a plurality of renewable energy power systems includes measuring, at least, a voltage, an active power, and a reactive power at a point of interconnection of the renewable energy farm to the power grid. The method also includes determining a sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection. Further, the method includes determining the grid strength of the power grid as a function of the sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection. In addition, the method includes dynamically determining at least one of an active power command or a reactive power command for the renewable energy farm at the point of interconnection based on the grid strength. Moreover, the method includes distributing at least one of the active power command or the reactive power command to individual controllers of the plurality of renewable energy power systems and a farm-level controller of the renewable energy farm.

18 Claims, 8 Drawing Sheets



(52) **U.S. Cl.**
CPC *G05B 2219/2619* (2013.01); *G05B 2219/2639* (2013.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,780,595	B2	7/2014	Larsen	
8,823,192	B2	9/2014	Bech	
8,872,372	B2	10/2014	Larsen et al.	
8,942,856	B2	1/2015	Ren et al.	
9,093,928	B2	7/2015	Larsen	
9,190,845	B2	11/2015	Nelson et al.	
9,243,613	B2	1/2016	Yin	
2013/0079945	A1	3/2013	Achilles et al.	
2014/0021720	A1	1/2014	Nelson et al.	
2014/0043080	A1	2/2014	Larsen	
2014/0100705	A1	4/2014	Shi et al.	
2014/0159367	A1	6/2014	Yin	
2014/0312620	A1	10/2014	Korber et al.	
2015/0025860	A1	1/2015	Andresen et al.	
2015/0137518	A1	5/2015	Yin et al.	
2015/0148974	A1*	5/2015	Diedrichs	G05B 15/02 700/287
2015/0369217	A1*	12/2015	Gupta	H02H 3/006 290/44

FOREIGN PATENT DOCUMENTS

EP	1841037		10/2007
EP	2175540		4/2010
EP	2236820	A2	10/2010
EP	2876768	A1	5/2015
EP	2963757	A1	1/2016
WO	WO2015179139	A1	11/2015
WO	WO2016062316	A1	4/2016
WO	WO 2017223222		12/2017
WO	WO2017223222	A1	12/2017
WO	WO 2018115431		6/2018

OTHER PUBLICATIONS

Arif et al., Online Predictive Model Fitting Algorithm for Supply Inductance Estimation, Energy Conversion Congress and Exposition (ECCE) 2015 IEEE, Montreal, QC, Sep. 2015, pp. 1595-1602.

European Search Report, dated May 18, 2020 for EP Application No. 20168835.5.

* cited by examiner

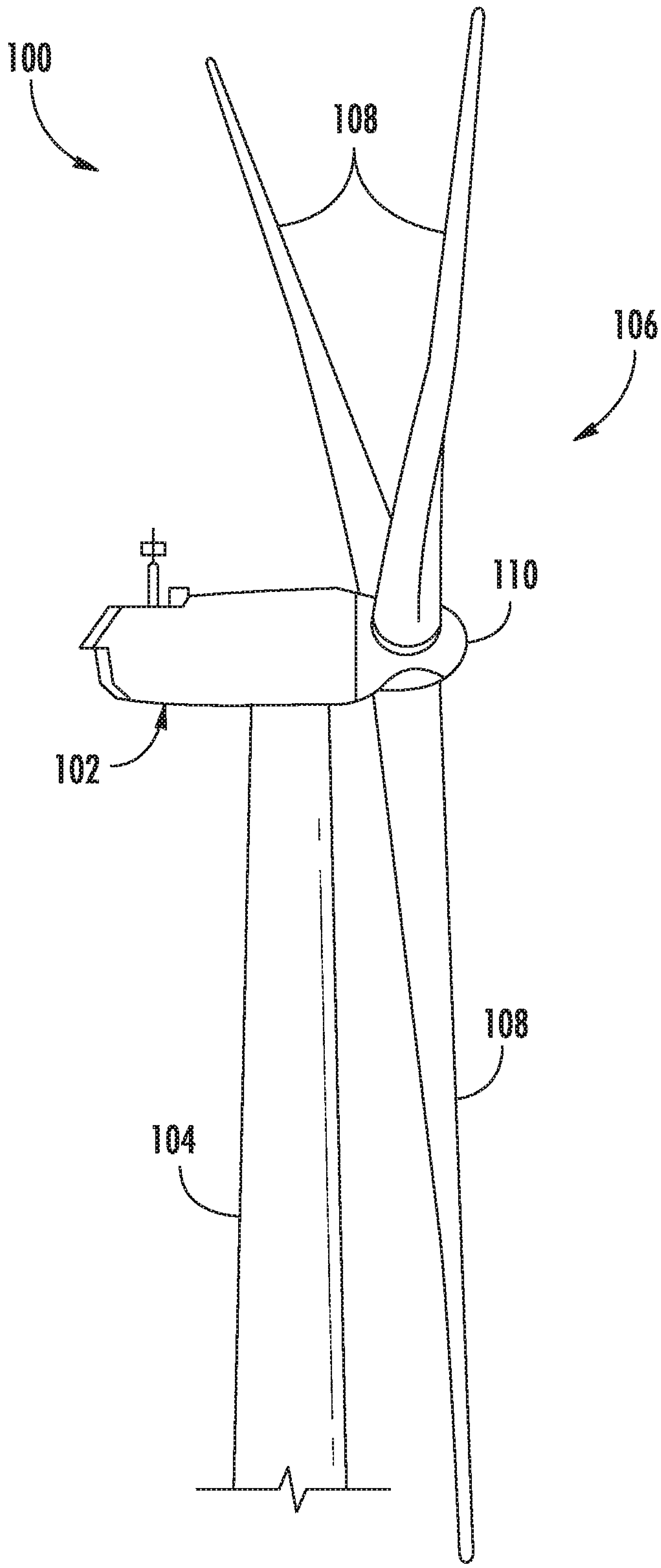


FIG. 1

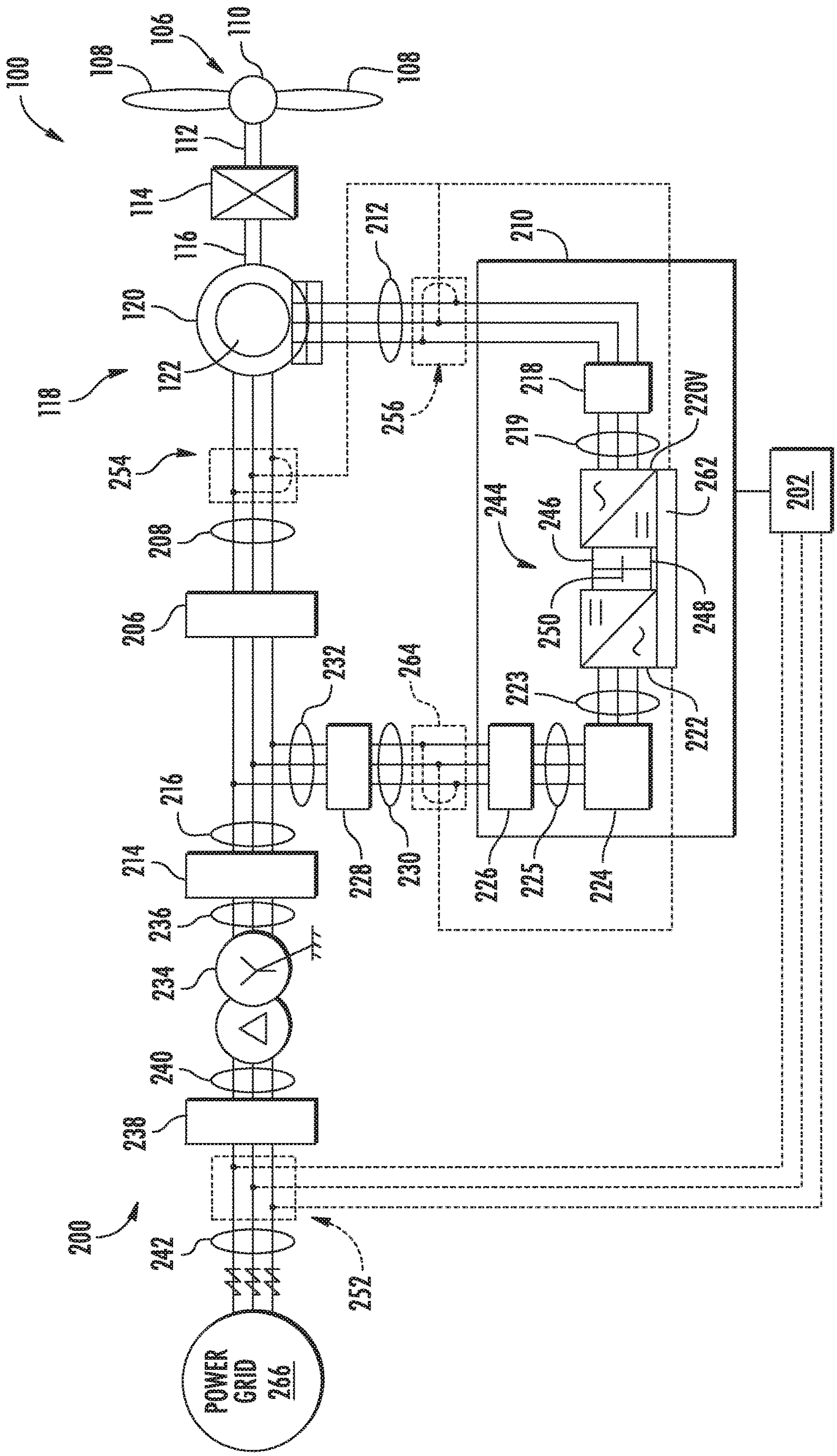

100
106
108
110
108
112
114
116
120
122
118
212
210
256
218
219
220V
254
262
244
246
202
208
206
250
248
232
264
223
222
216
214
228
230
226
225
224
236
234
240
238
200
242
252
POWER
GRID
266

FIG. 2

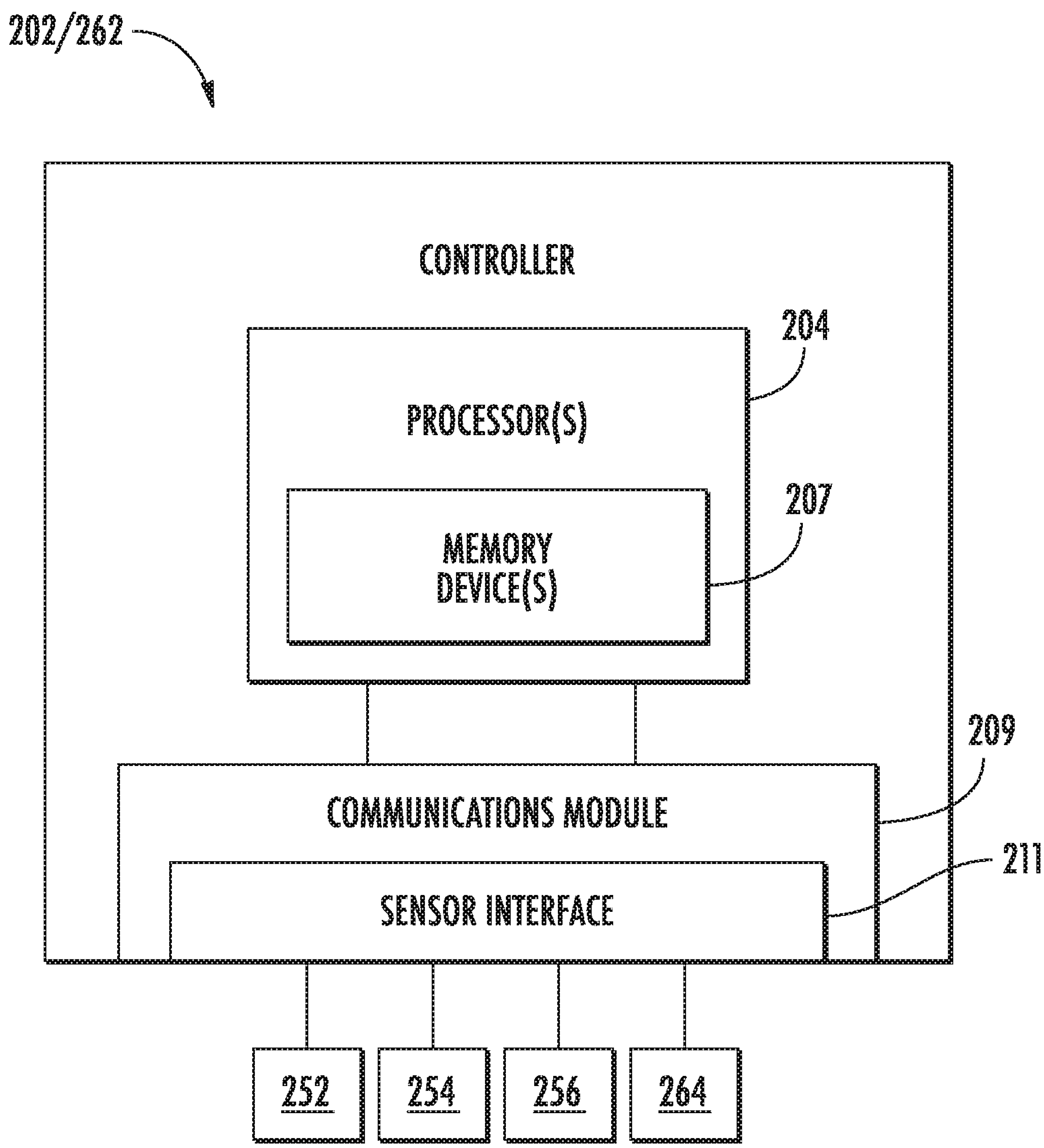

202/262
CONTROLLER
204
PROCESSOR(S)
207
MEMORY DEVICE(S)
209
COMMUNICATIONS MODULE
211
SENSOR INTERFACE
252
254
256
264

FIG. 3

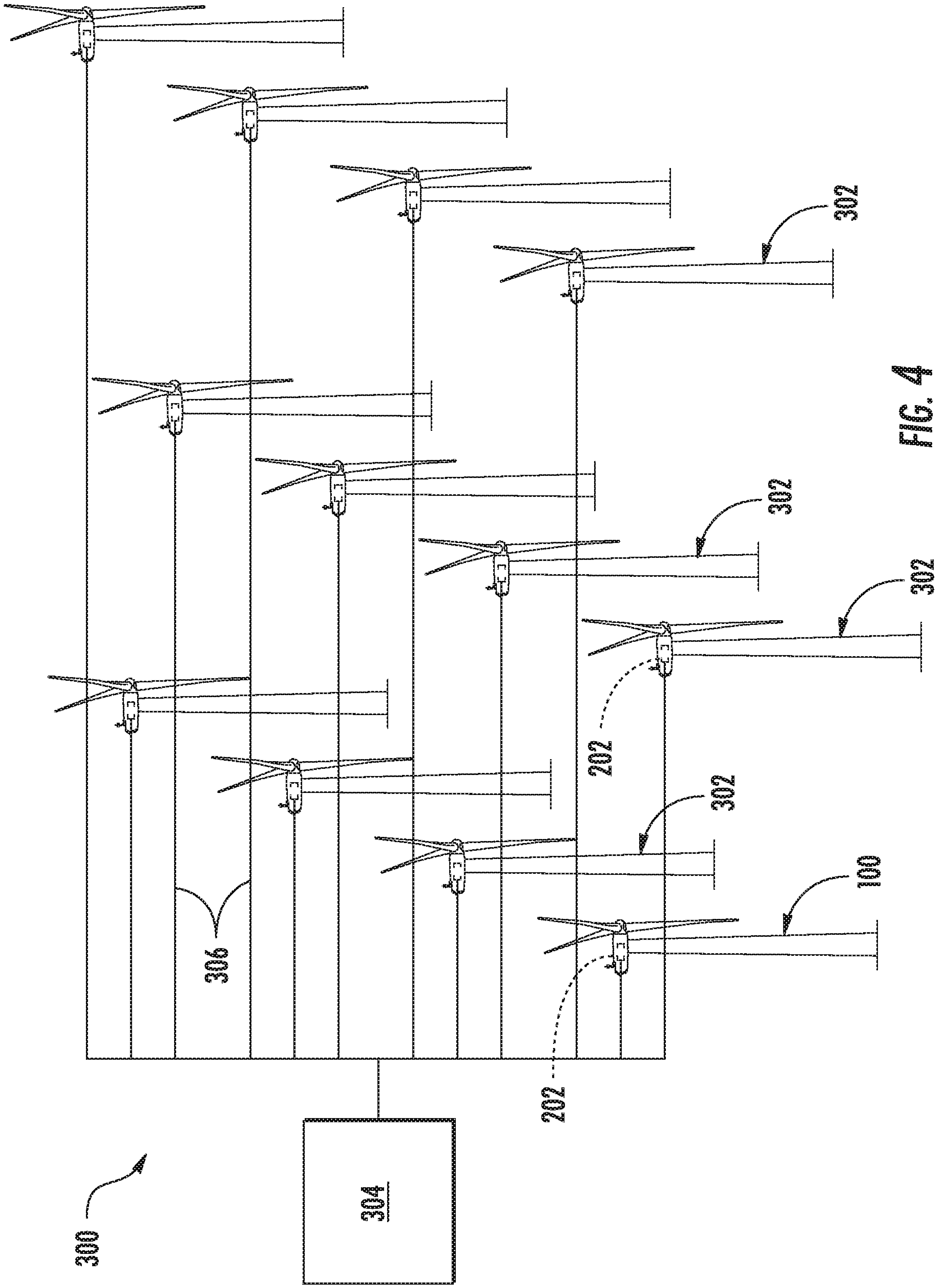


FIG. 4

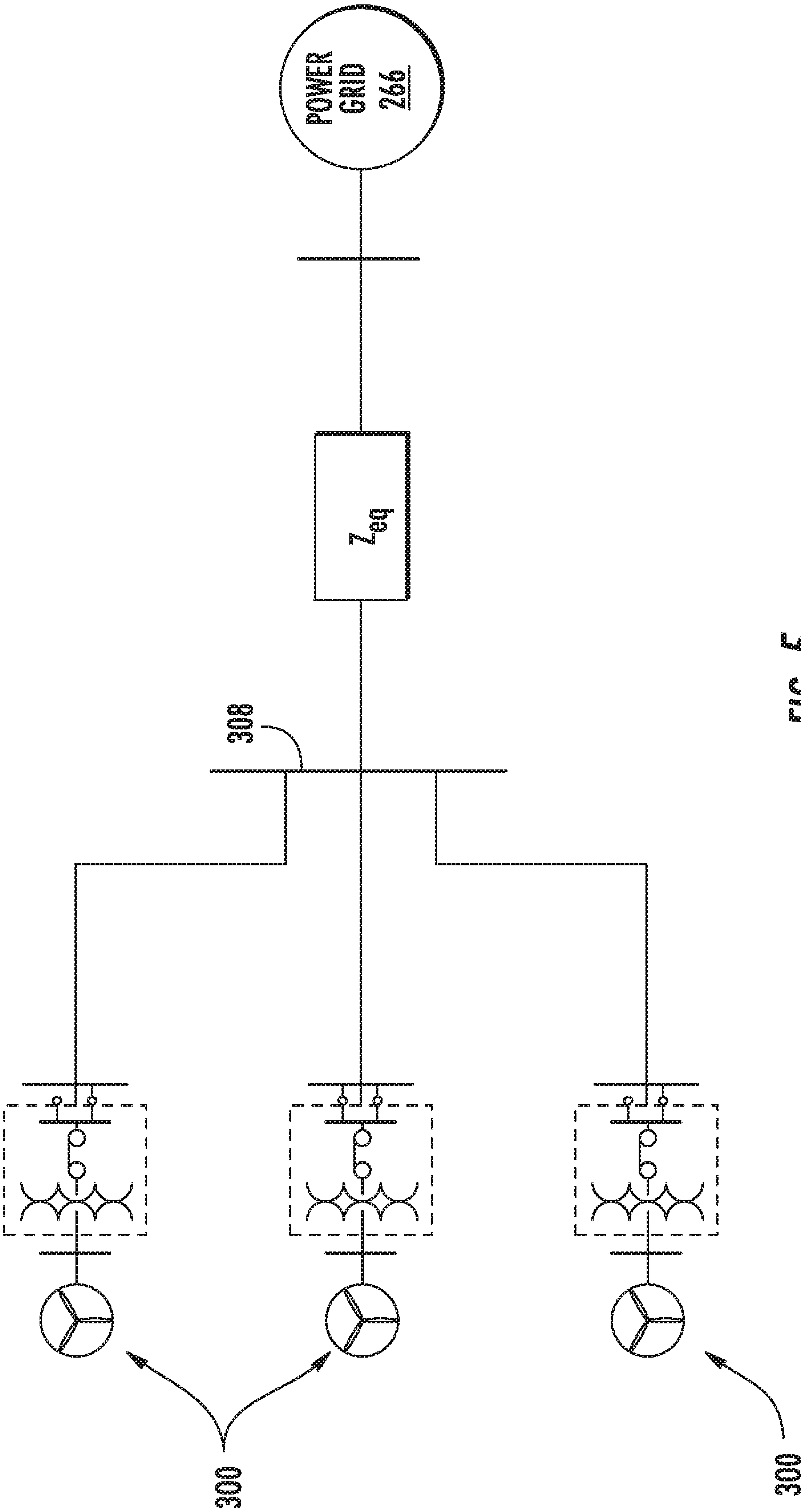


FIG. 5

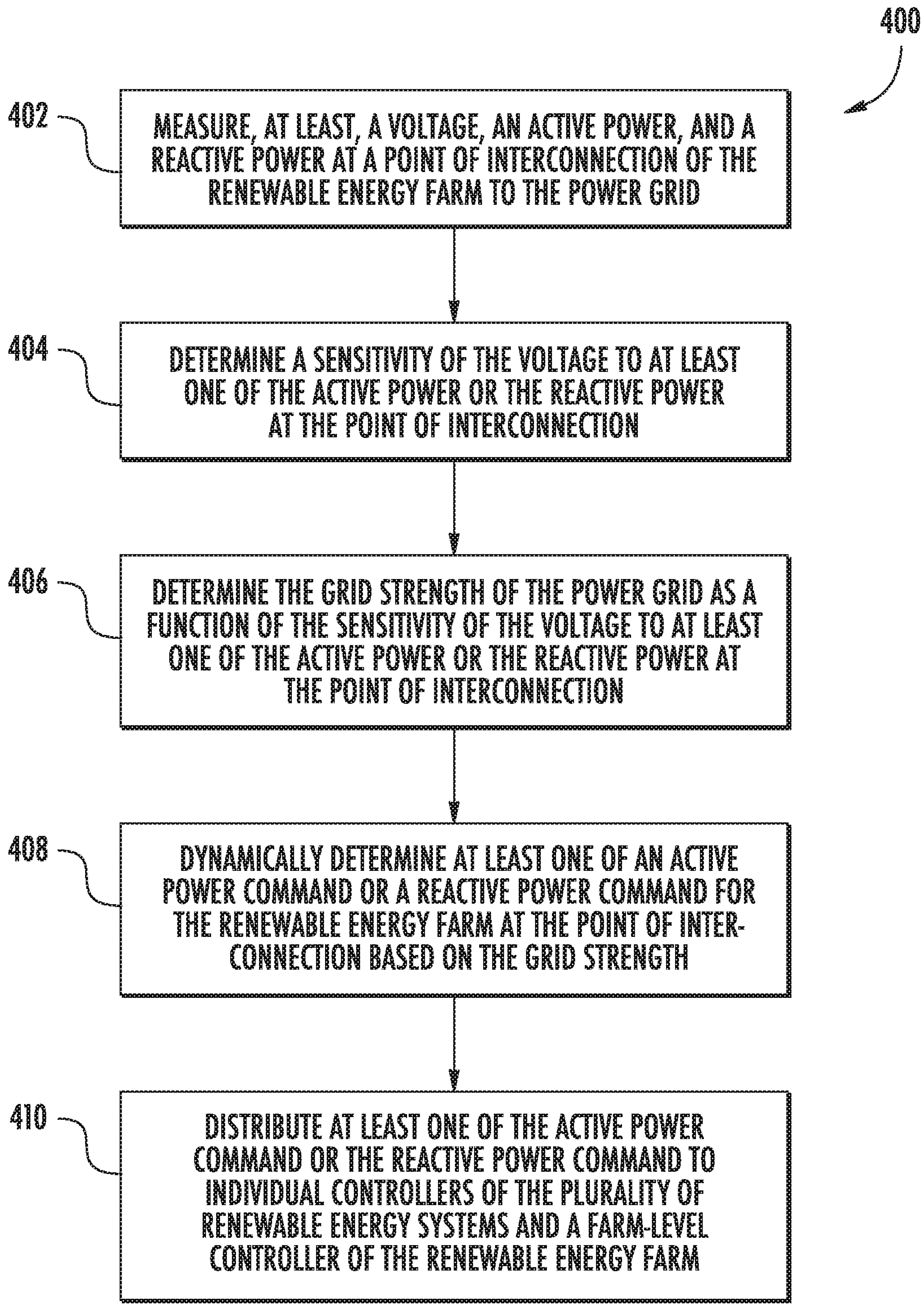

400
402
MEASURE, AT LEAST, A VOLTAGE, AN ACTIVE POWER, AND A REACTIVE POWER AT A POINT OF INTERCONNECTION OF THE RENEWABLE ENERGY FARM TO THE POWER GRID
404
DETERMINE A SENSITIVITY OF THE VOLTAGE TO AT LEAST ONE OF THE ACTIVE POWER OR THE REACTIVE POWER AT THE POINT OF INTERCONNECTION
406
DETERMINE THE GRID STRENGTH OF THE POWER GRID AS A FUNCTION OF THE SENSITIVITY OF THE VOLTAGE TO AT LEAST ONE OF THE ACTIVE POWER OR THE REACTIVE POWER AT THE POINT OF INTERCONNECTION
408
DYNAMICALLY DETERMINE AT LEAST ONE OF AN ACTIVE POWER COMMAND OR A REACTIVE POWER COMMAND FOR THE RENEWABLE ENERGY FARM AT THE POINT OF INTER-CONNECTION BASED ON THE GRID STRENGTH
410
DISTRIBUTE AT LEAST ONE OF THE ACTIVE POWER COMMAND OR THE REACTIVE POWER COMMAND TO INDIVIDUAL CONTROLLERS OF THE PLURALITY OF RENEWABLE ENERGY SYSTEMS AND A FARM-LEVEL CONTROLLER OF THE RENEWABLE ENERGY FARM

FIG. 6

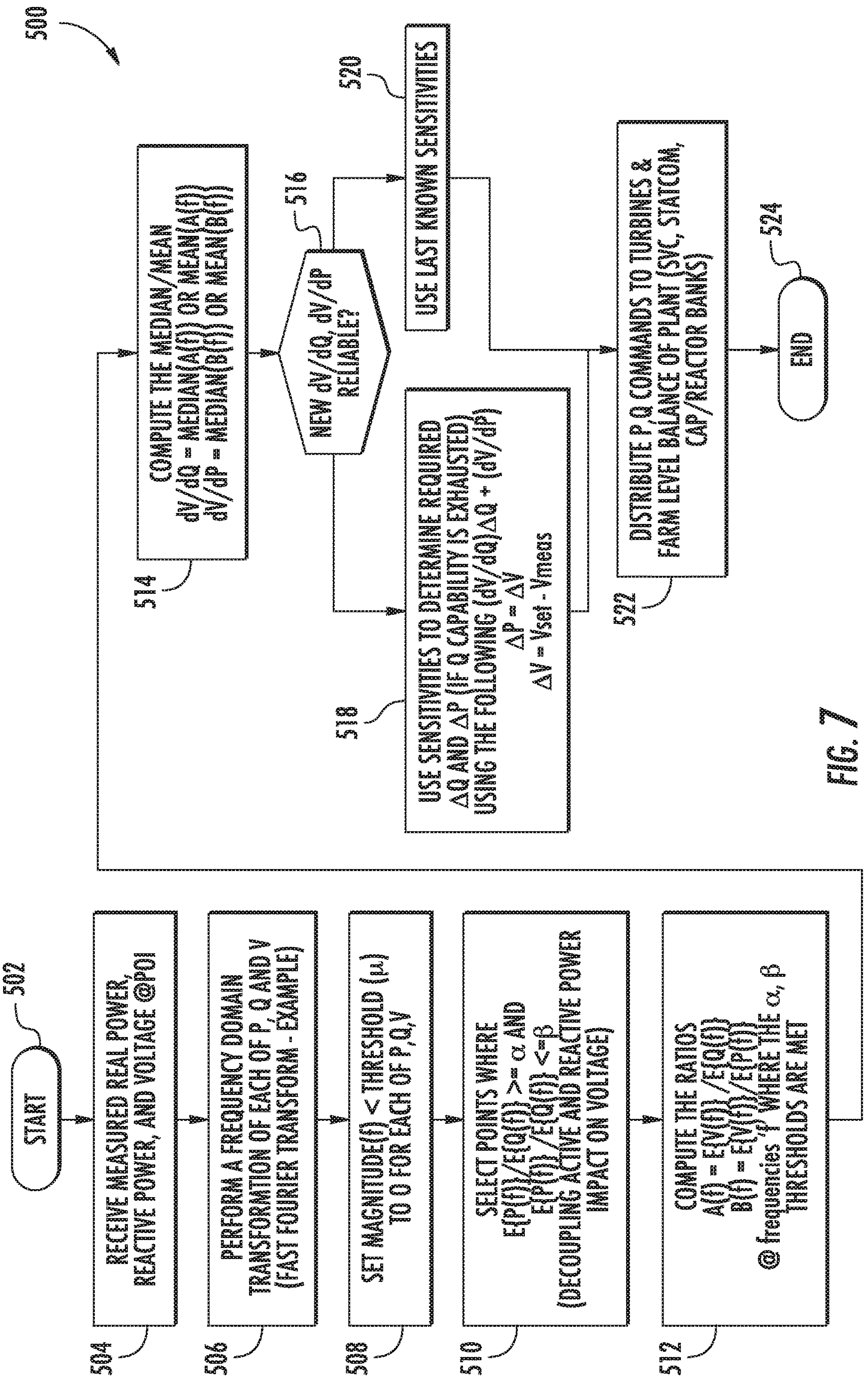

500
START
502
RECEIVE MEASURED REAL POWER, REACTIVE POWER, AND VOLTAGE @POI
504
PERFORM A FREQUENCY DOMAIN TRANSFORMATION OF EACH OF P, Q AND V (FAST FOURIER TRANSFORM - EXAMPLE)
506
SET MAGNITUDE(f) < THRESHOLD (μ) TO 0 FOR EACH OF P,Q,V
508
SELECT POINTS WHERE E(P(f))/E(Q(f)) >= α AND E(P(f))/E(Q(f)) <= β (DECOUPLING ACTIVE AND REACTIVE POWER IMPACT ON VOLTAGE)
510
COMPUTE THE RATIOS A(f) = E(V(f))/E(Q(f)) B(f) = E(V(f))/E(P(f)) @ frequencies f WHERE THE α, β THRESHOLDS ARE MET
512
COMPUTE THE MEDIAN/MEAN dV/dQ = MEDIAN(A(f)) OR MEAN(A(f)) dV/dP = MEDIAN(B(f)) OR MEAN(B(f))
514
NEW dV/dQ, dV/dP RELIABLE?
516
USE SENSITIVITIES TO DETERMINE REQUIRED ΔQ AND ΔP (IF Q CAPABILITY IS EXHAUSTED) USING THE FOLLOWING (dV/dQ)ΔQ + (dV/dP) ΔP = ΔV ΔV = Vset - Vmeas
518
USE LAST KNOWN SENSITIVITIES
520
DISTRIBUTE P,Q COMMANDS TO TURBINES & FARM LEVEL BALANCE OF PLANT (SVC, STATCOM, CAP/REACTOR BANKS)
522
END
524

FIG. 7

600

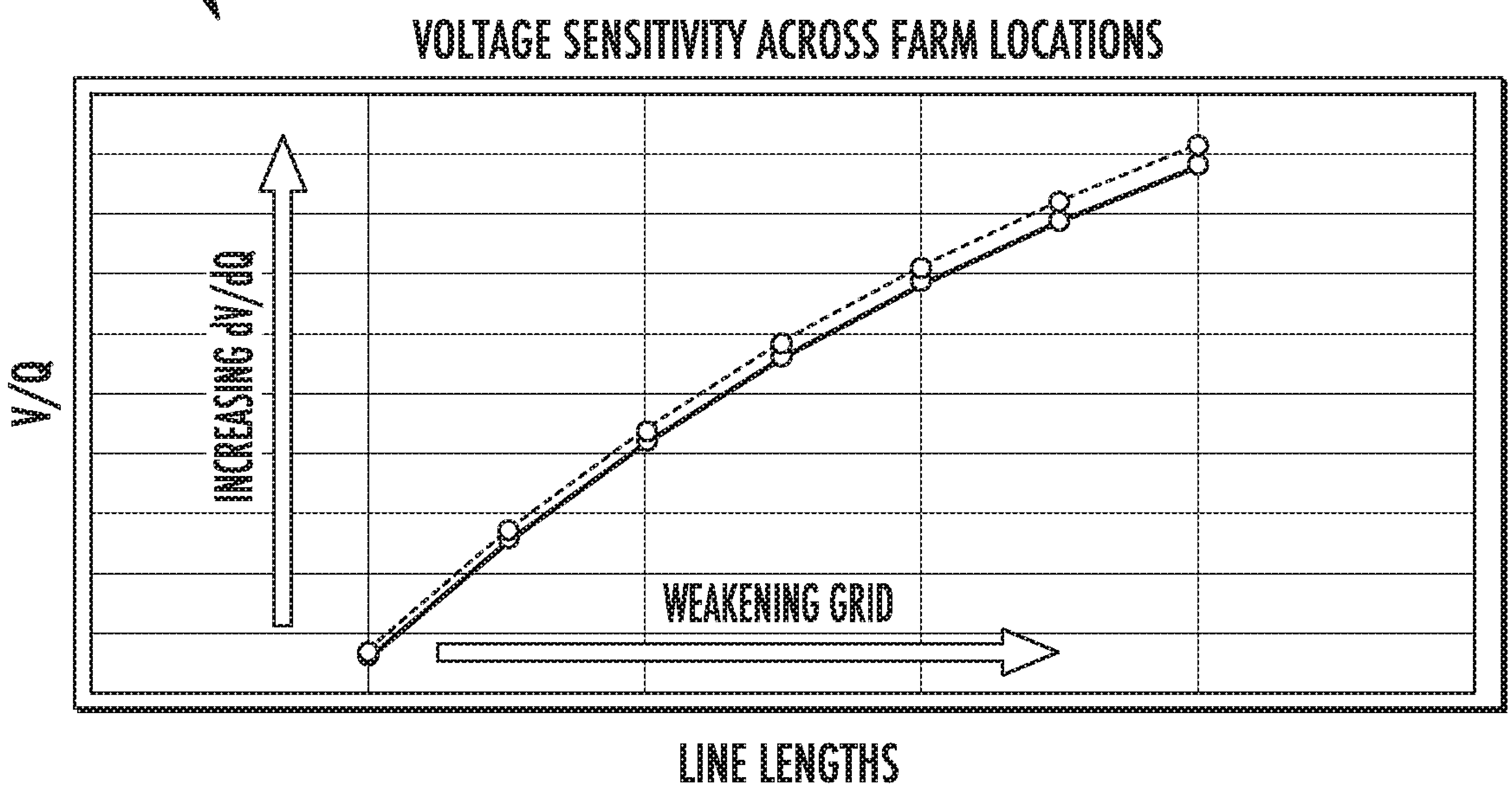

VOLTAGE SENSITIVITY ACROSS FARM LOCATIONS
V/Q
INCREASING dV/dQ
WEAKENING GRID
LINE LENGTHS

FIG. 8

SYSTEM AND METHOD FOR ESTIMATING GRID STRENGTH

FIELD

The present disclosure relates generally to renewable energy farms, such as wind farm, and more particular to a system and method for estimating grid strength of a power grid connected to a renewable energy farm.

BACKGROUND

Wind power is considered one of the cleanest, most environmentally friendly energy sources presently available, and wind turbines have gained increased attention in this regard. A modern wind turbine typically includes a tower, generator, gearbox, nacelle, and one or more rotor blades. The rotor blades capture kinetic energy of wind using known airfoil principles. For example, rotor blades typically have the cross-sectional profile of an airfoil such that, during operation, air flows over the blade producing a pressure difference between the sides. Consequently, a lift force, which is directed from a pressure side towards a suction side, acts on the blade. The lift force generates torque on the main rotor shaft, which is geared to a generator for producing electricity.

During operation, wind impacts the rotor blades and the blades transform wind energy into a mechanical rotational torque that rotatably drives a low-speed shaft. The low-speed shaft is configured to drive the gearbox that subsequently steps up the low rotational speed of the low-speed shaft to drive a high-speed shaft at an increased rotational speed. The high-speed shaft is generally rotatably coupled to a generator so as to rotatably drive a generator rotor. As such, a rotating magnetic field may be induced by the generator rotor and a voltage may be induced within a generator stator that is magnetically coupled to the generator rotor. The associated electrical power can be transmitted to a main transformer that is typically connected to a power grid via a grid breaker. Thus, the main transformer steps up the voltage amplitude of the electrical power such that the transformed electrical power may be further transmitted to the power grid.

In many wind turbines, the generator may be electrically coupled to a bi-directional power converter that includes a rotor-side converter joined to a line-side converter via a regulated DC link. Further, wind turbine power systems may include a variety of generator types, including but not limited to a doubly-fed induction generator (DFIG).

With increasing penetration of renewables, transmission upgrades lag generation addition leading to a situation where the grid capability (strength) worsens with increased capacity addition. From an operational standpoint, wind farms will be connected to grid with reduced short circuit capability (weaker grid) leading to challenges such as voltage stability and power evacuation capability in contingency situations. The short circuit ratio or grid strength is typically assessed offline during planning stage, while the true grid strength varies based on grid operating states (loading level, compensation sub-systems, line outages etc.).

In view of the foregoing, it would also be advantageous to provide an improved system and method for estimating grid strength in real time.

BRIEF DESCRIPTION

Aspects and advantages of the invention will be set forth in part in the following description, or may be obvious from the description, or may be learned through practice of the invention.

In one aspect, the present disclosure is directed to a method for estimating grid strength of a power grid connected to a renewable energy farm having a plurality of renewable energy power systems. The method includes measuring, at least, a voltage, an active power, and a reactive power at a point of interconnection of the renewable energy farm to the power grid. The method also includes determining a sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection. Further, the method includes determining the grid strength of the power grid as a function of the sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection. In addition, the method includes dynamically determining at least one of an active power command or a reactive power command for the renewable energy farm at the point of interconnection based on the grid strength. Moreover, the method includes distributing at least one of the active power command or the reactive power command to individual controllers of the plurality of renewable energy power systems and a farm-level controller of the renewable energy farm.

In one embodiment, the sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection increases with a weakening of the power grid. Further, the weakening of the power grid corresponds to a decrease in a short circuit ratio of a generator of the renewable energy farm.

In another embodiment, the renewable energy farm may be closely coupled to neighboring renewable energy farms. In such embodiments, each of the neighboring renewable energy farms exhibits perturbations in power due to varying wind conditions and/or grid conditions. As such, the method further includes modeling the power grid as a linear time-invariant system.

In further embodiments, determining the grid strength of the power grid as a function of the sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection may include performing a frequency domain transformation of each of the voltage, the active power, and the reactive power of the renewable energy farm. For example, in certain embodiments, the frequency domain transformation may include a Fast Fourier Transform.

In additional embodiments, determining the grid strength of the power grid as a function of the sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection may include decoupling an impact of the active power on the voltage from an impact of the reactive power on the voltage. In several embodiments, the method may further include calculating a derivative of the active power with respect to the voltage and a derivative of the reactive power with respect to the voltage.

In certain embodiments, dynamically determining at least one of the active power command or the reactive power command for the renewable energy farm at the point of interconnection based on the grid strength may include dynamically determining the active power command and the reactive power command for the renewable energy farm at the point of interconnection as a function of the derivative of the active power with respect to the voltage and the derivative of the reactive power with respect to the voltage.

In yet another embodiment, the renewable energy farm may include at least one of a wind farm, a solar farm, and energy storage farm, or combinations thereof.

In another aspect, the present disclosure is directed to a method for estimating grid strength of a power grid connected to a renewable energy power system, such as a wind turbine. The method includes receiving, at least, a voltage from a point of interconnection of the renewable energy power system to the power grid. The method also includes determining a change in voltage in response to at least one of an active power injection or a reactive power injection at the point of interconnection. Further, the method includes determining the grid strength of the power grid as a function of the change in voltage in response to at least one of an active power injection or a reactive power injection at the point of interconnection. In addition, the method includes dynamically determining at least one of an active power command or a reactive power command for the renewable energy power system at the point of interconnection based on the grid strength. Moreover, the method includes distributing at least one of the active power command or the reactive power command to a controller of the renewable energy power system. It should also be understood that the method may further include any of the additional features and/or steps as described herein.

In yet another aspect, the present disclosure is directed to a system for estimating grid strength of a power grid connected to a wind farm having a plurality of wind turbines. The system includes one or more sensors communicatively coupled to a point of interconnection of the wind farm for measuring, at least, a voltage, an active power, and a reactive power. Further, the system includes a farm-level controller having at least one processor. The processor(s) is configured to perform a plurality of operations, including but not limited to determining a sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection, determining the grid strength of the power grid as a function of the sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection, and dynamically determining at least one of an active power command or a reactive power command for the wind farm at the point of interconnection based on the grid strength. Moreover, the method includes distributing at least one of the active power command or the reactive power command to individual controllers of the plurality of wind turbines. It should also be understood that the system may further include any of the additional features as described herein.

These and other features, aspects and advantages of the present invention will become better understood with reference to the following description and appended claims. The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

A full and enabling disclosure of the present invention, including the best mode thereof, directed to one of ordinary skill in the art, is set forth in the specification, which makes reference to the appended figures, in which:

FIG. **1** illustrates a perspective view of a portion of one embodiment of a wind turbine according to the present disclosure;

FIG. **2** illustrates a schematic view of one embodiment of an electrical and control system suitable for use with the wind turbine shown in FIG. **1**;

FIG. **3** illustrates a block diagram of one embodiment of suitable components that may be included in a controller according to the present disclosure;

FIG. **4** illustrates a schematic diagram of one embodiment of a wind farm according to the present disclosure;

FIG. **5** illustrates a schematic diagram of one embodiment of a plurality of wind farms connected to a power grid at a point of interconnection according to the present disclosure;

FIG. **6** illustrates a flow diagram of one embodiment of a method for estimating grid strength of a power grid connected to a wind farm according to the present disclosure;

FIG. **7** illustrates a flow diagram of one embodiment of an algorithm **500** that may be implemented by a controller for determining the grid strength of the power grid according to the present disclosure; and

FIG. **8** illustrates a graph of one embodiment of the relationship of derivatives of voltage with respect to real and reactive power and line lengths (x-axis) for a plurality of wind farms according to the present disclosure.

DETAILED DESCRIPTION

Reference now will be made in detail to embodiments of the invention, one or more examples of which are illustrated in the drawings. Each example is provided by way of explanation of the invention, not limitation of the invention. In fact, it will be apparent to those skilled in the art that various modifications and variations can be made in the present invention without departing from the scope or spirit of the invention. For instance, features illustrated or described as part of one embodiment can be used with another embodiment to yield a still further embodiment. Thus, it is intended that the present invention covers such modifications and variations as come within the scope of the appended claims and their equivalents.

Generally, the present disclosure is directed to a system and method for estimating voltage sensitivity to real or reactive power at a point of interconnection, which is indicative of the grid strength. Further, the system and method of the present disclosure is capable of reliably estimating the voltage sensitivity even in situations where multiple farms are closely coupled. Prior art methods only work reliably in situations where a farm is electrically distant from other farms and hence will have limited application in preventing voltage control based interactions between closely coupled wind farms. As such, the present disclosure utilizes frequency domain methods to derive the voltage sensitivity to active and reactive power injection by a wind farm.

Accordingly, the present disclosure has many advantages not present in the prior art. For example, wind farms connected to weak grids (i.e. having a low short circuit ratio (SCR)) exhibit an inability to transfer active power and reactive power generated by its wind turbines. While transferring power into the weak grid, the POI and turbine terminal voltages may rise beyond designed limits and thus it is inevitable to curtail active power, reactive power, or both to bring voltages back within limits. Curtailment of active power decreases annual energy production (AEP) of the wind farm and hence loss in revenue for the customer. Voltage control performance of the wind farm is also affected by the grid strength especially where farms are clustered close together. Stable operation may require sacrificial trips on the wind turbines, which can be avoided by estimating the voltage sensitivity and tuning controls based on the real-time estimate as described herein.

Referring now to the drawings, FIG. **1** illustrates a perspective view of a portion of an exemplary wind turbine **100** according to the present disclosure that is configured to implement the method and apparatus as described herein. The wind turbine **100** includes a nacelle **102** that typically houses a generator (not shown). The nacelle **102** is mounted on a tower **104** having any suitable height that facilitates operation of wind turbine **100** as described herein. The wind turbine **100** also includes a rotor **106** that includes three blades **108** attached to a rotating hub **110**. Alternatively, the wind turbine **100** may include any number of blades **108** that facilitates operation of the wind turbine **100** as described herein.

Referring to FIG. **2**, a schematic view of an exemplary electrical and control system **200** that may be used with the wind turbine **100** is illustrated. During operation, wind impacts the blades **108** and the blades **108** transform wind energy into a mechanical rotational torque that rotatably drives a low-speed shaft **112** via the hub **110**. The low-speed shaft **112** is configured to drive a gearbox **114** that subsequently steps up the low rotational speed of the low-speed shaft **112** to drive a high-speed shaft **116** at an increased rotational speed. The high-speed shaft **116** is generally rotatably coupled to a generator **118** so as to rotatably drive a generator rotor **122**. In one embodiment, the generator **118** may be a wound rotor, three-phase, double-fed induction (asynchronous) generator (DFIG) that includes a generator stator **120** magnetically coupled to a generator rotor **122**. As such, a rotating magnetic field may be induced by the generator rotor **122** and a voltage may be induced within a generator stator **120** that is magnetically coupled to the generator rotor **122**. In one embodiment, the generator **118** is configured to convert the rotational mechanical energy to a sinusoidal, three-phase alternating current (AC) electrical energy signal in the generator stator **120**. The associated electrical power can be transmitted to a main transformer **234** via a stator bus **208**, a stator synchronizing switch **206**, a system bus **216**, a main transformer circuit breaker **214**, and a generator-side bus **236**. The main transformer **234** steps up the voltage amplitude of the electrical power such that the transformed electrical power may be further transmitted to a power grid **266** via a breaker-side bus **240**, a grid circuit breaker **238**, and a grid bus **242**.

The generator stator **120** may be electrically coupled to a stator synchronizing switch **206** via a stator bus **208**. In one embodiment, to facilitate the DFIG configuration, the generator rotor **122** is electrically coupled to a bi-directional power conversion assembly **210** or power converter via a rotor bus **212**. Alternatively, the generator rotor **122** may be electrically coupled to the rotor bus **212** via any other device that facilitates operation of electrical and control system **200** as described herein. In a further embodiment, the stator synchronizing switch **206** may be electrically coupled to a main transformer circuit breaker **214** via a system bus **216**.

The power conversion assembly **210** may include a rotor filter **218** that is electrically coupled to the generator rotor **122** via the rotor bus **212**. A rotor filter bus **219** electrically couples the rotor filter **218** to a rotor-side power converter **220**. Further, the rotor-side power converter **220** may be electrically coupled to a line-side power converter **222** via a single direct current (DC) link **244**. Alternatively, the rotor-side power converter **220** and the line-side power converter **222** may be electrically coupled via individual and separate DC links. In addition, as shown, the DC link **244** may include a positive rail **246**, a negative rail **248**, and at least one capacitor **250** coupled therebetween.

In addition, a line-side power converter bus **223** may electrically couple the line-side power converter **222** to a line filter **224**. Also, a line bus **225** may electrically couple the line filter **224** to a line contactor **226**. Moreover, the line contactor **226** may be electrically coupled to a conversion circuit breaker **228** via a conversion circuit breaker bus **230**. In addition, the conversion circuit breaker **228** may be electrically coupled to the main transformer circuit breaker **214** via system bus **216** and a connection bus **232**. The main transformer circuit breaker **214** may be electrically coupled to an electric power main transformer **234** via a generator-side bus **236**. The main transformer **234** may be electrically coupled to a grid circuit breaker **238** via a breaker-side bus **240**. The grid circuit breaker **238** may be connected to the electric power transmission and distribution grid via a grid bus **242**.

During operation, alternating current (AC) power generated at the generator stator **120** by rotation of the rotor **106** is provided via a dual path to the grid bus **242**. The dual paths are defined by the stator bus **208** and the rotor bus **212**. On the rotor bus side **212**, sinusoidal multi-phase (e.g. three-phase) AC power is provided to the power conversion assembly **210**. The rotor-side power converter **220** converts the AC power provided from the rotor bus **212** into DC power and provides the DC power to the DC link **244**. Switching elements (e.g. IGBTs) used in bridge circuits of the rotor side power converter **220** can be modulated to convert the AC power provided from the rotor bus **212** into DC power suitable for the DC link **244**.

The line side converter **222** converts the DC power on the DC link **244** into AC output power suitable for the electrical grid bus **242**. In particular, switching elements (e.g. IGBTs) used in bridge circuits of the line side power converter **222** can be modulated to convert the DC power on the DC link **244** into AC power on the line side bus **225**. The AC power from the power conversion assembly **210** can be combined with the power from the stator **120** to provide multi-phase power (e.g. three-phase power) having a frequency maintained substantially at the frequency of the electrical grid bus **242** (e.g. 50 Hz/60 Hz). It should be understood that the rotor-side power converter **220** and the line-side power converter **222** may have any configuration using any switching devices that facilitate operation of electrical and control system **200** as described herein.

Further, the power conversion assembly **210** may be coupled in electronic data communication with a converter controller **262** and/or a turbine controller **202** configured to control the operation of the rotor-side power converter **220** and the line-side power converter **222**. For example, during operation, the controller **202** may be configured to receive one or more voltage and/or electric current measurement signals from a first set of voltage and electric current sensors **252**. Thus, the controller **202** may be configured to monitor and control at least some of the operational variables associated with the wind turbine **100** via the sensors **252**. In the illustrated embodiment, each of the sensors **252** may be electrically coupled to each one of the three phases of grid bus **242**. Alternatively, the sensors **252** may be electrically coupled to any portion of electrical and control system **200** that facilitates operation of electrical and control system **200** as described herein. In addition to the sensors described above, the sensors may also include a second set of voltage and electric current sensors **254**, a third set of voltage and electric current sensors **256**, a fourth set of voltage and electric current sensors **264** (all shown in FIG. **2**), and/or any other suitable sensors. Further, the voltage and electric current sensors **252**, **254**, **256**, **264** may be configured to measure, directly or indirectly, a power output of the wind turbine **100**.

In addition, the converter controller **262** is configured to receive one or more voltage and electric current measurement signals. For example, as shown in the illustrated embodiment, the converter controller **262** receives voltage and electric current measurement signals from the second set of voltage and electric current sensors **254** coupled in electronic data communication with stator bus **208**. The converter controller **262** may also receive the third and fourth set of voltage and electric current measurement signals from the third and fourth set of voltage and electric current sensors **256**, **264**. In addition, the converter controller **262** may be configured with any of the features described herein in regards to the turbine controller **202**. Further, the converter controller **262** may be separate from or integral with the turbine controller **202**.

Thus, the wind turbine controller **202**, as well as the converter controller **262**, is configured to control various components of the wind turbine **100**. Accordingly, as shown particularly in FIG. **3**, the controller(s) **202**, **262** may include one or more processor(s) **204** and associated memory device(s) **207** configured to perform a variety of computer-implemented functions (e.g., performing the methods, steps, calculations and the like and storing relevant data as disclosed herein). Additionally, the controller **202** may also include a communications module **209** to facilitate communications between the controller **202** and the various components of the wind turbine **100**, e.g. any of the components of FIG. **2**. Further, the communications module **209** may include a sensor interface **211** (e.g., one or more analog-to-digital converters) to permit signals transmitted from one or more sensors to be converted into signals that can be understood and processed by the processors **204**. It should be appreciated that the sensors (e.g. sensors **252**, **254**, **256**, **264**) may be communicatively coupled to the communications module **209** using any suitable means. For example, as shown in FIG. **3**, the sensors **252**, **254**, **256**, **264** may be coupled to the sensor interface **211** via a wired connection. However, in other embodiments, the sensors **252**, **254**, **256**, **264** may be coupled to the sensor interface **211** via a wireless connection, such as by using any suitable wireless communications protocol known in the art. As such, the processor **204** may be configured to receive one or more signals from the sensors.

As used herein, the term "processor" refers not only to integrated circuits referred to in the art as being included in a computer, but also refers to a controller, a microcontroller, a microcomputer, a programmable logic controller (PLC), an application specific integrated circuit, and other programmable circuits. The processor **204** is also configured to compute advanced control algorithms and communicate to a variety of Ethernet or serial-based protocols (Modbus, OPC, CAN, etc.). Additionally, the memory device(s) **207** may generally comprise memory element(s) including, but not limited to, computer readable medium (e.g., random access memory (RAM)), computer readable non-volatile medium (e.g., a flash memory), a floppy disk, a compact disc-read only memory (CD-ROM), a magneto-optical disk (MOD), a digital versatile disc (DVD) and/or other suitable memory elements. Such memory device(s) **207** may generally be configured to store suitable computer-readable instructions that, when implemented by the processor(s) **204**, configure the controller **202** to perform the various functions as described herein.

It should also be understood that any number or type of sensors may be employed within the wind turbine **100** and at any location. For example, the sensors as described herein may be temperature sensors, Micro Inertial Measurement Units (MIMUs), strain gauges, accelerometers, pressure sensors, humidity sensors, speed sensors, strain gauges, accelerometers, airflow sensors, angle of attack sensors, vibration sensors, Light Detecting and Ranging (LIDAR) sensors, camera systems, fiber optic systems, anemometers, wind vanes, Sonic Detection and Ranging (SODAR) sensors, infra lasers, radiometers, pitot tubes, rawinsondes, other optical sensors, and/or any other suitable sensors.

Referring now to FIG. **4**, it should also be understood that the wind turbine **100** described herein may be part of a wind farm **300** according to present disclosure. As shown, the wind farm **300** may include a plurality of wind turbines **302**, including the wind turbine **100** described above, and a farm-level controller **304**. For example, as shown in the illustrated embodiment, the wind farm **300** includes twelve wind turbines, including wind turbine **100**. However, in other embodiments, the wind farm **300** may include any other number of wind turbines, such as less than twelve wind turbines or greater than twelve wind turbines. In other embodiments, other sources of energy generation such as solar, chemical, geothermal, and/or thermal generation with or without energy storage devices may also be added to the wind farm **300**. In one embodiment, the controller **202** of the wind turbine **100** may be communicatively coupled to the farm-level controller **304** through a wired connection, such as by connecting the farm-level controller **304** through suitable communicative links **306** or networks (e.g., a suitable cable). Alternatively, the controller **202** may be communicatively coupled to the farm-level controller **304** through a wireless connection, such as by using any suitable wireless communications protocol known in the art. Further, the farm-level controller **304** may be generally configured similar to the controller **202** for each of the individual wind turbines **302** within the wind farm **300**.

In addition, as shown in FIG. **5**, a plurality of the wind farms **300** may be connected to the power grid **266** at a point of interconnection (POI) **308**. In such embodiments, as shown, the wind farm **300** may be closely coupled to other neighboring wind farms **300**. In such embodiments, each of the neighboring renewable energy farms **300** exhibits perturbations in power due to varying wind conditions and/or grid conditions. As such, frequency domain methods can be used to decouple the perturbations in power from neighboring wind farms **300** to reduce the influence of the perturbations in power from the neighboring wind farms **300** on the locally measured voltage. Further, for a short-term time period, (e.g. a few seconds), the power grid **266** can be reasonably assumed to be a linear time-invariant system. Therefore, the controller(s) **202**, **304** may be configured to model the power grid **266** as a linear time-invariant system, which evaluates the response of a linear and time-invariant system (e.g. the active or reactive power) to an arbitrary input signal (e.g. voltage). In such instances, the perturbations in power at certain frequencies will translate to changes in voltage at the same frequency. Methods for using frequency domain methods to decouple the perturbations in power from neighboring wind farms **300** and for estimating grid strength of the power grid **266** are described below with respect to FIGS. **6-8**.

Referring now to FIG. **6**, a flow diagram of one embodiment of a method **400** for estimating grid strength of a power grid connected to a renewable energy farm is illustrated. The method **400** may be implemented to, for instance, with the wind turbine **100** and/or wind farm **300** discussed above with reference to FIGS. **1-6**. FIG. **7** depicts steps performed in a particular order for purposes of illustration and discussion. Those of ordinary skill in the art, using the disclosures provided herein, will understand that various steps of the method **400** or any of the other methods disclosed herein may be adapted, modified, rearranged, performed simultaneously or modified in various ways without deviating from the scope of the present disclosure.

As shown at (**402**), the method **400** includes measuring, at least, a voltage, an active power, and a reactive power at the point of interconnection **308** of the wind farm **300** (also referred to herein as a renewable energy farm) to the power grid **266**. As shown at (**404**), the method **400** includes determining a sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection **308**. In one embodiment, the sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection increases with a weakening of the power grid **266**. Further, the weakening of the power grid **266** corresponds to a decrease in a short circuit ratio of the generator **120** of the wind farm **300**.

As shown at (**406**), the method **400** includes determining the grid strength of the power grid **266** as a function of the sensitivity of the voltage to the active power and/or the reactive power at the point of interconnection **308**. More specifically, FIG. **7** illustrates a flow diagram of one embodiment of an algorithm **500** that may be implemented by the controller(s) **202**, **304** for determining the grid strength of the power grid **266**. As shown at (**502**), the algorithm **500** starts. As shown at (**504**), the algorithm **500** receives the measured real power, reactive power, and voltage from the POI **308**. As shown at (**506**), the controller(s) **202**, **304** are configured to determine the grid strength of the power grid **266** by performing a frequency domain transformation of each of the voltage (V), the active power (P), and the reactive power (Q) of the wind farm **300**. For example, in certain embodiments, the frequency domain transformation may include a Fast Fourier Transform. As shown at (**508**), the algorithm **500** may include setting a magnitude (f) less than a threshold (μ) to zero (0) for each of the voltage (V), the active power (P), and the reactive power (Q) of the wind farm **300**. As shown at (**510**), the algorithm **500** may include selecting points herein E{P(f)}/E{Q(f)} is greater than or equal to a and E{P(f)}/E{Q(f)} is less than or equal to β, which has the effect of decoupling the active and reactive power impact on the voltage. As shown at (**512**), the algorithm **500** may include computing various ratios of voltage with respect to reactive and real power (e.g. A(f)=E{V(f)}/E{Q(f) and B(f)=E{V(f)}/E{P(f)}) at frequencies "f" where the α, β thresholds are met.

As shown at (**514**), the algorithm **500** may also include computing the median/mean of the ratios from (**512**) to determine derivatives thereof (e.g. dV/dQ=median (A(f)) or mean (A(f)) and dV/dP=median (B(f)) or mean (B(f))). The derivatives (e.g. dV/dQ and dV/dP) represent the sensitivity of the voltage to the active power and/or the reactive power at the point of interconnection **308**. For example, as shown in FIG. **8**, a graph **600** of one embodiment of the relationship of the derivatives (e.g. dV/dQ and dV/dP) (y-axis) with respect to line lengths (x-axis) for a plurality of wind farms **300** is illustrated. As shown, increasing derivatives (e.g. dV/dQ and dV/dP) correspond with a weakening grid/SCR. Therefore, by calculating the derivatives (e.g. dV/dQ and dV/dP), the controller(s) **202**, **304** can determine the grid strength. As shown at (**516**), the algorithm **500** is further configured to determine whether the derivatives (e.g. dV/dQ and dV/dP) are reliable. If so, the algorithm **500** moves to (**518**) as further described below. If not, as shown at (**520**), the algorithm **500** utilizes the last known sensitivities.

Thus, referring back to FIG. **6**, as shown at (**408**), the method **400** includes dynamically determining at least one of an active power command or a reactive power command for the wind farm **300** at the point of interconnection based on the grid strength. Thus, as shown at (**410**), the method **400** also includes distributing the active power command and/or the reactive power command to the individual controllers **202** of the plurality of wind turbines **302** and the farm-level controller **304** of the wind farm **300**. For example, in certain embodiments, dynamically determining at least one of the active power command or the reactive power command for the wind farm **300** at the point of interconnection **308** based on the grid strength may include dynamically determining the active power command and the reactive power command for the wind farm **300** at the point of interconnection **308** as a function of the derivative of the active power with respect to the voltage and the derivative of the reactive power with respect to the voltage.

More specifically, as shown at (**518**) of FIG. **5**, the controller(s) **202**, **304** can use the sensitivities (e.g. the derivatives) to determine the required delta Q (e.g. ΔQ) and delta P (e.g. ΔP) (if Q capability is exhausted) using, for example, the Equations (1) and (2) below:

$$(dV/DQ)\Delta Q+(dV/DP)\Delta P=\Delta V$$

$$\Delta V=V\text{set}-V\text{meas}$$

Where ΔV is the change in voltage at the point of interconnection **308**,

Vset is the voltage set point at the point of interconnection **308**, and

Vmeas is the measured voltage at the point of interconnection **308**.

Referring still to FIG. **7**, at shown at (**522**), the algorithm **500** then includes distributing the active P and reactive Q power commands to the individual wind turbine controllers **202** and farm-level controller **304**. As shown at (**524**), the algorithm **500** ends.

Although the various methods and algorithms described herein are generally explained with respect to farm-level control, it should also be understood that the same methods and algorithms can also be used to obtain sensitivities at the turbine level by utilizing turbine level measurements, although the estimates may be comparatively more noisy. In such instances, further processing can be completed to reduce noise, including, for example, filtering, etc.

Exemplary embodiments of a wind turbine, a control system for a wind turbine, and methods of controlling a wind turbine are described above in detail. The methods, wind turbine, and control system are not limited to the specific embodiments described herein, but rather, components of the wind turbine and/or the control system and/or steps of the methods may be utilized independently and separately from other components and/or steps described herein. For example, the control system and methods may also be used in combination with other wind turbine power systems and methods, and are not limited to practice with only the power system as described herein. Rather, the exemplary embodiment can be implemented and utilized in connection with many other wind turbine or power system applications, such as solar power systems and energy storage power systems.

Although specific features of various embodiments of the invention may be shown in some drawings and not in others, this is for convenience only. In accordance with the principles of the invention, any feature of a drawing may be referenced and/or claimed in combination with any feature of any other drawing.

This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they include structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

What is claimed is:

1. A method for estimating grid strength of a power grid connected to a renewable energy farm having a plurality of renewable energy power systems, the method comprising:

measuring, at least, a voltage, an active power, and a reactive power at a point of interconnection of the renewable energy farm to the power grid;

determining a sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection;

determining the grid strength of the power grid as a function of the sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection by performing a frequency domain transformation of each of the voltage, the active power, and the reactive power of the renewable energy farm;

dynamically determining at least one of an active power command or a reactive power command for the renewable energy farm at the point of interconnection based on the grid strength; and,

distributing at least one of the active power command or the reactive power command to individual controllers of the plurality of renewable energy systems and a farm-level controller of the renewable energy farm.

2. The method of claim **1**, wherein the sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection increases with a weakening of the power grid.

3. The method of claim **2**, wherein the weakening of the power grid corresponds to a decrease in a short circuit ratio of a generator of the renewable energy farm.

4. The method of claim **1**, wherein the renewable energy farm is coupled to neighboring renewable energy farms, each of the neighboring renewable energy farms exhibiting perturbations in power due to varying wind conditions and/or grid conditions, the method further comprising modeling the power grid as a linear time-invariant system.

5. The method of claim **1**, wherein the frequency domain transformation comprises a Fast Fourier Transform.

6. The method of claim **5**, wherein determining the grid strength of the power grid as a function of the sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection further comprises:

decoupling an impact of the active power on the voltage from an impact of the reactive power on the voltage.

7. The method of claim **6**, further comprising calculating a derivative of the active power with respect to the voltage and a derivative of the reactive power with respect to the voltage.

8. The method of claim **7**, wherein dynamically determining at least one of the active power command or the reactive power command for the renewable energy farm at the point of interconnection based on the grid strength further comprises:

dynamically determining the active power command and the reactive power command for the renewable energy farm at the point of interconnection as a function of the derivative of the active power with respect to the voltage and the derivative of the reactive power with respect to the voltage.

9. The method of claim **1**, wherein the renewable energy farm comprises at least one of a wind farm, a solar farm, and energy storage farm, or combinations thereof.

10. A method for estimating grid strength of a power grid connected to a renewable energy power system, the method comprising:

receiving, at least, a voltage from a point of interconnection of the renewable energy power system to the power grid;

determining a change in voltage in response to at least one of an active power injection or a reactive power injection at the point of interconnection;

determining the grid strength of the power grid as a function of the change in voltage in response to at least one of an active power injection or a reactive power injection at the point of interconnection by performing a frequency domain transformation of each of the voltage, the active power, and the reactive power of the renewable energy farm;

dynamically determining at least one of an active power command or a reactive power command for the renewable energy power system at the point of interconnection based on the grid strength; and,

distributing at least one of the active power command or the reactive power command to a controller of the renewable energy power system.

11. A system for estimating grid strength of a power grid connected to a wind farm having a plurality of renewable energy power systems, the system comprising:

one or more sensors communicatively coupled to a point of interconnection of the wind farm for measuring, at least, a voltage, an active power, and a reactive power;

a farm-level controller comprising at least one processor, the processor configured to perform a plurality of operations, the plurality of operations comprising:

determining a sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection;

determining the grid strength of the power grid as a function of the sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection by performing a frequency domain transformation of each of the voltage, the active power, and the reactive power of the renewable energy farm;

dynamically determining at least one of an active power command or a reactive power command for the wind farm at the point of interconnection based on the grid strength; and,

distributing at least one of the active power command or the reactive power command to individual controllers of the plurality of wind turbines.

12. The system of claim **11**, wherein the sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection increases with a weakening of the power grid.

13. The system of claim **11**, wherein a weakening of the power grid corresponds to a decrease in a short circuit ratio of a generator of the wind farm.

14. The system of claim **11**, wherein the wind farm is coupled to neighboring wind farms, each of the neighboring wind farms exhibiting perturbations in power due to varying wind conditions and/or grid conditions, the method further comprising modeling the power grid as a linear time-invariant system.

15. The system of claim **11**, wherein the frequency domain transformation comprises a Fast Fourier Transform.

16. The system of claim **15**, wherein determining the grid strength of the power grid as a function of the sensitivity of the voltage to at least one of the active power or the reactive power at the point of interconnection further comprises:

decoupling an impact of the active power on the voltage from an impact of the reactive power on the voltage.

17. The system of claim **16**, further comprising calculating a derivative of the active power with respect to the voltage and a derivative of the reactive power with respect to the voltage.

18. The system of claim **17**, wherein dynamically determining at least one of the active power command or the reactive power command for the wind farm at the point of interconnection based on the grid strength further comprises:

dynamically determining the active power command and the reactive power command for the wind farm at the point of interconnection as a function of the derivative of the active power with respect to the voltage and the derivative of the reactive power with respect to the voltage.

* * * * *